Novel metrology for measuring spectral purity of KrF lasers for deep UV lithography

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ABSTRACT

The use of higher NA lenses of next generation 248 nm microlithography systems sets tight requirements on the spectral purity of the laser, especially because these lenses are not chromatically corrected. Present day KrF excimer lasers are equipped with etalon-based spectrometers that can measure the laser linewidth at full-width-at-half-maximum ($\Delta\lambda_{FWHM}$), at nearly every pulse. Both, experience and analysis has shown that the $\Delta\lambda_{FWHM}$ may not be the optimum measure of laser spectral purity, and that a better characterization would be the width of the line that contains 95% of the laser energy, $\Delta\lambda_{95\%}$. Therefore, the lithographer is at risk of losing the image quality if the line shape, characterized by $\Delta\lambda_{95\%}$. is outside its limit, even if the laser signals that the $\Delta\lambda_{FWHM}$ is within limits. In this paper, we describe the results of our development of new generation spectrometers that are capable of making simultaneous, high resolution $\Delta\lambda_{FWHM}$ and $\Delta\lambda_{95\%}$ measurements of laser line shape. The measurements can be done on a pulse-to-pulse basis or with averaging over exposure window. Several different configurations and their comparable analysis are presented. These new spectrometers are compact, and can be integrated with a deep UV laser or used as a portable field service tool. Despite the small size, the spectrometers have a resolution of about 0.1 pm when measuring FWHM values and about 0.3 pm when measuring 95% integral values. The implementation of these new metrology tools provides the lithographer with a correct measure of the laser spectral purity during exposure and during process optimization.

Keywords: DUV lithography, metrology, spectral width, spectrometers, KrF excimer laser, line-narrowing

1. INTRODUCTION

The optical configuration of a refractive stepper or scanner imaging optics has undergone significant changes in this past decade. In particular, the lens NA have increased steadily, and today, the expected NA is about 0.7. In KrF, the use of NA = 0.7 lens would enhance the resolution of 248nm lithography down to about 0.18 μm levels[1,2] (and may, fortuitously, delay the introduction of 193nm lithography). Since these lenses will not be chromatically corrected, the linewidth requirements increase significantly as the NA increases. For a fused silica lens of NA = 0.7, the linewidth requirement at full-width-at-half-maximum ($\Delta\lambda_{FWHM}$) is about 0.6 pm[3] .

The effect of laser linewidth in a lens is to cause a “blurring” of the image, often described by the parameter – Modulation Transfer Function[4]. Both, experience and analysis have shown that the $\Delta\lambda_{FWHM}$ may not be the optimum measure of laser spectral purity, and that a better characterization would be the width of the line that contains 95% of the laser energy, $\Delta\lambda_{95\%}$. In other words, $\Delta\lambda_{95\%}$ specification of the spectrum limits the maximum amount of energy contained in the tails or the maximum spectral range that contains the majority of the light energy. Such characterizations are becoming increasingly important as high NA lenses are being pushed to their resolution limit. For example, for NA = 0.7 lens, the required $\Delta\lambda_{95\%}$ bandwidth is about 2.0 pm.

Present KrF excimer lasers for DUV lithography are capable of meeting these specs, but continuous monitoring of the laser bandwidth is required to insure high yield[5]. Currently, an etalon-based spectrometers are typically used for continuous bandwidth measurements during laser operation. These instruments can measure laser $\Delta\lambda_{FWHM}$ at nearly every pulse. During exposure, the laser confirms that the $\Delta\lambda_{FWHM}$ is within its specification, and signals the stepper or scanner accordingly. From our aforementioned discussions, the lithographer is at risk of losing the image quality if the laser spectrum line shape, characterized by $\Delta\lambda_{95\%}$. is outside its limit, even if the laser signals that the $\Delta\lambda_{FWHM}$ is within limits.

In this paper, we describe novel spectrometers that are capable of making simultaneous high resolution $\Delta\lambda_{FWHM}$ and $\Delta\lambda_{95\%}$ measurements of laser line shape on a pulse-by-pulse basis. The tools are compact such that it can be integrated with a DUV laser. Most importantly, they provides the lithographer a correct measure of the laser spectral purity during exposure and during process optimization.

2. λ_{FWHM} SPECTRAL MEASUREMENTS WITH ETALON SPECTROMETER

Fig. 1 shows a typical etalon spectrometer used for linewidth measurements. The sample of the laser beam goes through a diffuser and then illuminates an etalon. Usually, the air space etalon is used, with the etalon plates typically coated to reflect about 90 - 95% of light. The transmitted light through the etalon is collected by a lens and focused onto a PDA array, where a set of fringes is formed. The signal from the PDA is read by a laser microprocessor. The intensity of transmitted light along the angle α to the etalon is determined by the following equations[6]:

$$I_t = I_0 / (1 + (2F/p)^2 \sin^2 (d/2)) \,, \tag{1}$$

$$F = pR^{1/2} / (1 - R) \,, \tag{2}$$

$$d = 2p\, Ds / l + Df \,, \tag{3}$$

$$Ds = 2dn_a \cos a . \tag{4}$$

In these equations, I_0 is the incident light intensity, δ is the phase shift, Df is extra phase shift on reflection from the etalon surface, λ is the laser wavelength, d is the etalon gap, F is the etalon finesse, n_a is the refractive index of gas filing the gap, a is the incident angle. As a result, a set of concentric fringes is formed with radii satisfying equations (1) - (4). The spacing between the fringes is determined by an etalon FSR value:

$$FSR = l^2 / 2nd. \tag{5}$$

By proper choice of FSR and etalon finesse F, an accurate measurements of laser spectral bandwidth at FWHM level can be done. Unfortunately, this etalon spectrometer is not a very good tool to measure the spectrum shape, in particular, to accurately measure the spectrum tails. This is because the slit function of the etalon spectrometer as described by eqs. (1) - (4) does not provide enough resolution for the measurement of the tails of the laser spectrum.

Fig. 2. shows a calculated slit function of the etalon spectrometer. The etalon spectrometer has FSR = 5 pm, and finesse F = 38. For the etalon spectrometer to accurately measure spectrum of the laser, the resolution of the spectrometer should be significantly better than the laser spectrum. While this condition is satisfied for $\Delta\lambda_{FWHM}$ measurements, where etalon slit function FWHM of 0.13 pm is substantially smaller than typical laser $\Delta\lambda_{FWHM}$ of about 0.6 pm, the same is not true for $\Delta\lambda_{95\%\ int}$ measurements, where

the etalon slit function bandwidth of about 1.5 pm is comparable with the expected laser bandwidth of about 2 pm. Therefor, if such an instrument is used to measure $\Delta\lambda_{95\%\ int}$, a heavy deconvolution is needed to get a real $\Delta\lambda_{95\%\ int}$ value. Such analysis is prone to errors and ambiguous results, so really no reliable $\Delta\lambda_{95\%\ int}$ information is available during the lithography process. As a result, a laser can go out of specification unnoticed. This can lead to very expensive yield problems and should be avoided.

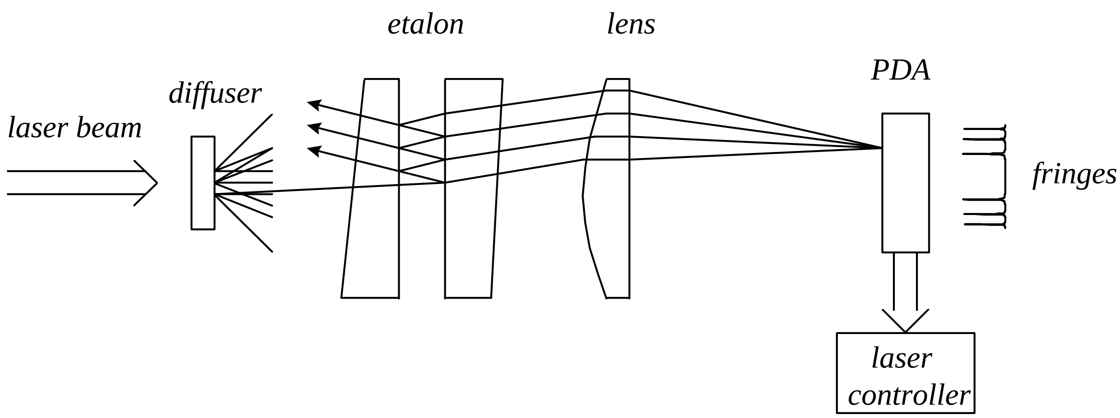

Fig. 1. Optical scheme of an etalon spectrometer.

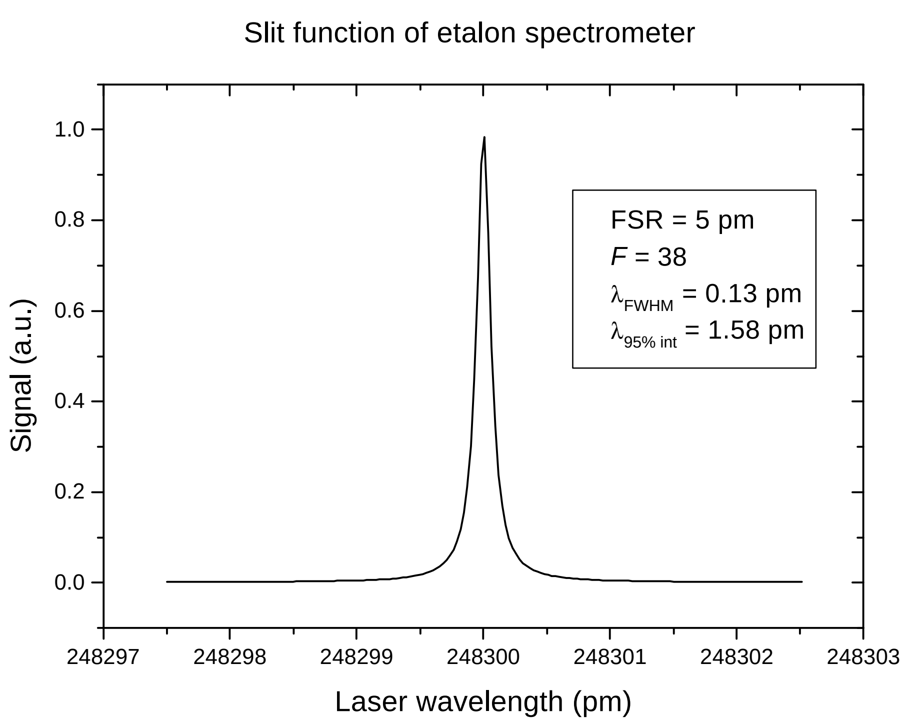

Fig. 2. Slit function of conventional etalon spectrometer. FSR = 5 pm, finesse F = 38.

3. SPECTRAL MEASUREMENTS WITH HIGH RESOLUTION GRATING SPECTROMETER

To accurately measure spectrum tails, a high resolution diffraction grating spectrometer can be used. Fig. 3 shows an optical scheme of such an instrument.

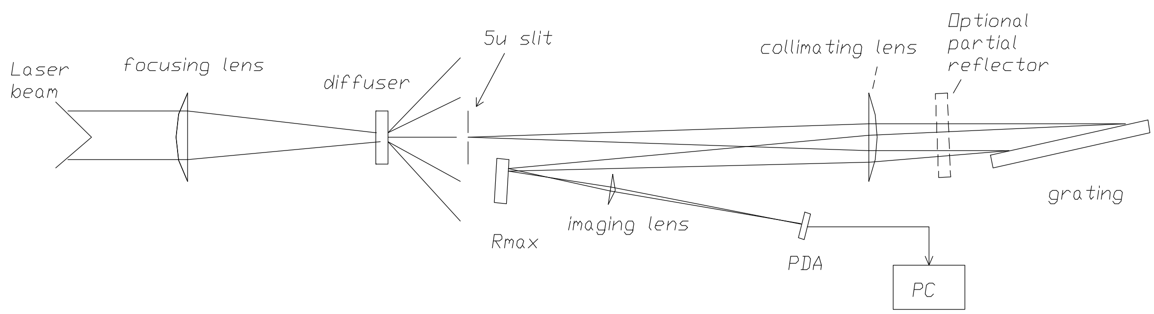

Fig. 3. High resolution grating spectrometer

A sample of laser beam is focused by a lens onto diffuser. The scattered light is directed onto the entrance slit of the instrument, which has a width of about 5μm. Light transmitted through the slit expands in the 5 μm direction (which is in the plane of drawing) and collimated by a collimating lens. The collimated beam illuminates diffraction grating which is arranged in a near Littrow configuration. The light reflected from the grating is focused by the collimating lens back to a line. Because this light is reflected at a small angle relative to direction of the incoming beam, a small mirror can be used to pick up the reflected light. An imaging lens can be used to magnify the slit image and transfer it onto a linear photo-diode array. The signal from this array can be read by a portable computer.

In the Littow configuration, the dispersion of diffraction grating is determined by

$$db / dl = m / (d_g \cos b), \qquad (6)$$

where b is the incidence angle, d_g is groove spacing, and m is diffraction order. The best resolution can be achieved when using echelle gratings working at high angles and high diffraction orders. If higher resolution is desired, this spectrometer can be converted into a double pass arrangement, by inserting a partially reflecting mirror between the collimating lens and the grating. The reflection of this mirror can be about 30%. The effect of this mirror is to reflect a portion of a beam, already reflected by grating, back to the grating for the second pass. This reflector is tilted at a small angle, so that single and double pass beams are angular separated. Of cause, this partial reflector will cause big losses, and reduction of double pass signal by as much as 90%, but usually, there is enough light available for spectral measurements even with such big losses. If so desired, a third or even higher pass can be used for even more accurate spectral measurements. These passes are generated in this arrangement by a light bouncing few times back and forth between the partially reflecting mirror and the grating.

The grating provides high resolution adequate for both $\Delta\lambda_{FWHM}$ and $\Delta\lambda_{95\%\ int}$ measurements. Fig. 4 shows a slit function of the instrument built by Cymer, Inc using an optical scheme similar to that of Fig. 3. A double pass configuration with a partial reflector is chosen as an example.

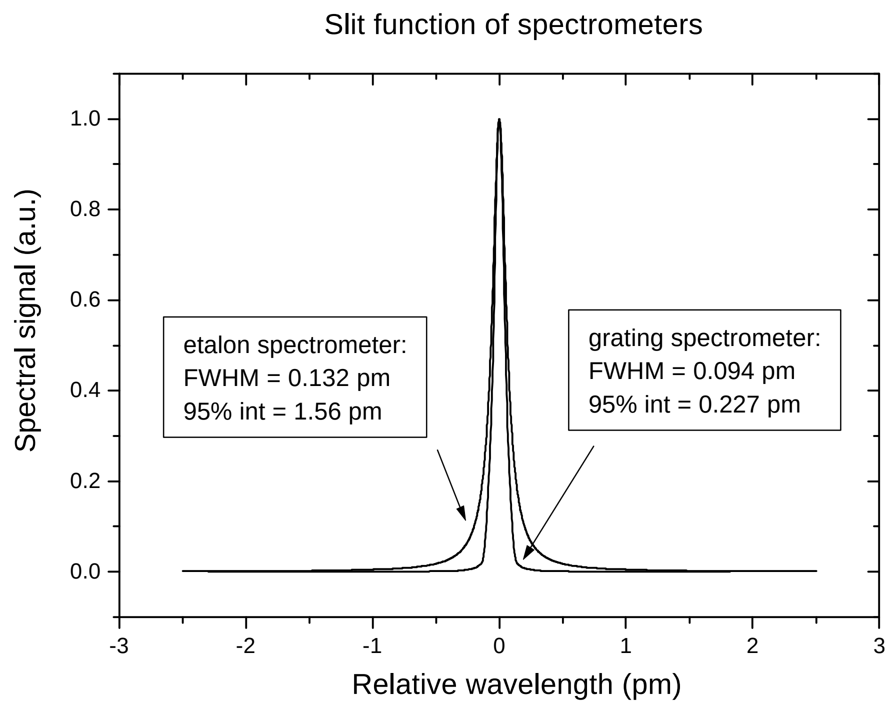

Fig. 4. Comparison of slit functions of etalon and grating spectrometers

For comparison, a slit function of etalon spectrometer is also shown in Fig. 4. The $\Delta\lambda_{FWHM}$ bandwidth of grating spectrometer slit function is 0.094 pm as compared with 0.132 pm for etalon spectrometer. The $\Delta\lambda_{95\%\ int}$ bandwidth of grating spectrometer slit function is 0.227 pm, which is about 5X improvement over etalon spectrometer. Therefore, both instruments can provide adequate resolution for $\Delta\lambda_{FWHM}$ measurements, but only grating spectrometer can provide an adequate resolution for $\Delta\lambda_{95\%int}$ measurements.

Unfortunately, high resolution grating spectrometers tend to be quite bulky and difficult to incorporate into the laser. The main size factors are the big focal length of the collimating lens as well as the size of the grating itself. Therefore, it is difficult to make these instruments portable, so that they can be integrated in the laser, or at least can be used as a portable field service tool. These instruments, however, can be successfully used at the factory during production and testing of excimer lithography lasers.

4. COMPACT HIGH RESOLUTION GRATING SPECTROMETER

It is a big technical challenge to make a compact high resolution grating spectrometer. Problems include mechanical stability of the compact system, possible optical distortion if extra optical components are used to fold the beam, problems of stray light, difficulties of alignment, etc. We have developed the compact version of the high resolution grating spectrometer, which would satisfy to all the requirements for industrial tool. We were using the basic scheme of Fig.3 but significant modifications to the basic design were done in order to reduce the overall size of the instrument. The prototype compact high resolution grating spectrometer was built, which fits in the box of 3’ x 1’ x 0.8’. This spectrometer can be attached to the diagnostic interface plate of Cymer ELS-50x0-series excimer laser as shown in Fig. 5. A laptop PC is

used to collect the data. The spectrometer is capable of measuring spectrum on a single shot basis or averaged over specified window. The capability of fast spectrum measurements allows to trace all the transients in the spectrum, associated, for example, with the laser heating up from the cold state. In a continuous acquisition

Fig. 5. Compact high resolution grating spectrometer shown installed on Cymer ELS-5000 KrF excimer laser.

mode, the laser spectrum is constantly monitored, which guarantees that the laser spectrum does not go out of specification at any time.

The resolution of this compact grating spectrometer have been tested using a frequency-doubled Ar-ion laser. This laser emits a very narrow line at 248.25 nm with $\Delta\lambda_{\text{FWHM}} < 0.01$ pm. When laser is in a single mode operation, expected $\Delta\lambda_{95\%\ \text{int}}$ is less than 0.03 pm. The spectrum of this laser, measured with our compact grating spectrometer is shown in Fig. 6.

As it can be seen from Fig. 6, the compact grating spectrometer provides adequate resolution for measuring both $\Delta\lambda_{\text{FWHM}}$ and $\Delta\lambda_{95\%\ \text{int}}$ values. Its slit function is close to the theoretical limits with $\Delta\lambda_{\text{FWHM}} = 0.1$ pm and $\Delta\lambda_{95\%\ \text{int}} = 0.31$ pm. Fig. 7 shows the comparison of the Cymer ELS-5000 excimer laser spectrum measured with this new tool and using Cymer standard high resolution grating spectrometer. Fig. 7 shows spectrums as measured, no deconvolution have been done. One can see, that both instruments give almost exactly the same results. We have tested the instrument over different ranges of laser operation and found very good agreement throughout the whole testing range.

The tool as it is right now is still fairly large, but it can be used as a field service tool. Some work on further size reduction is still needed, however, if it is to be installed in the laser without increasing the size of the laser enclosure. This development is currently underway.

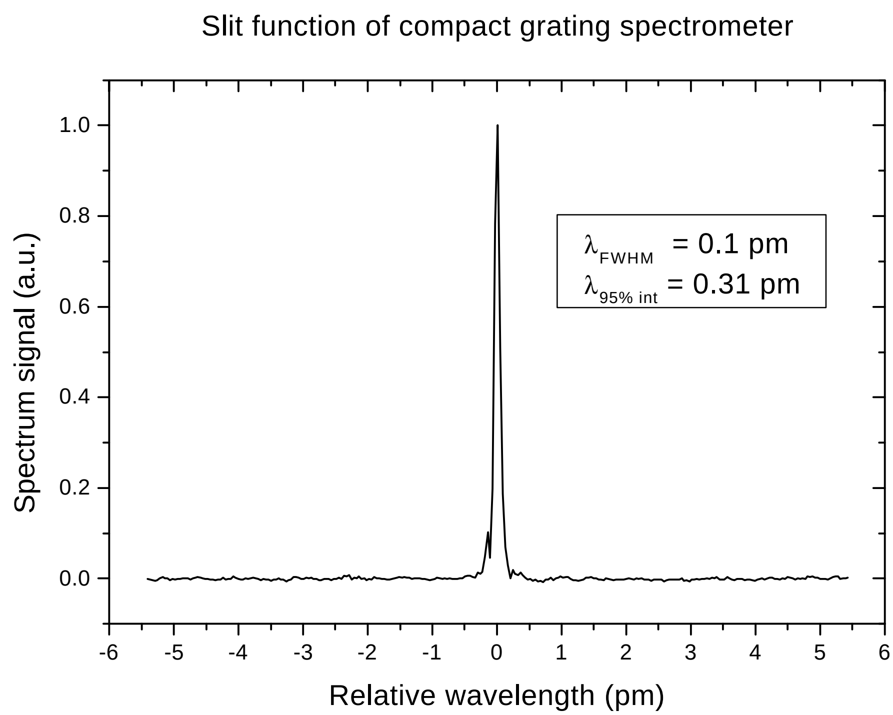

Fig. 6. Experimental slit function of compact grating spectrometer measured with frequency double Ar-ion laser.

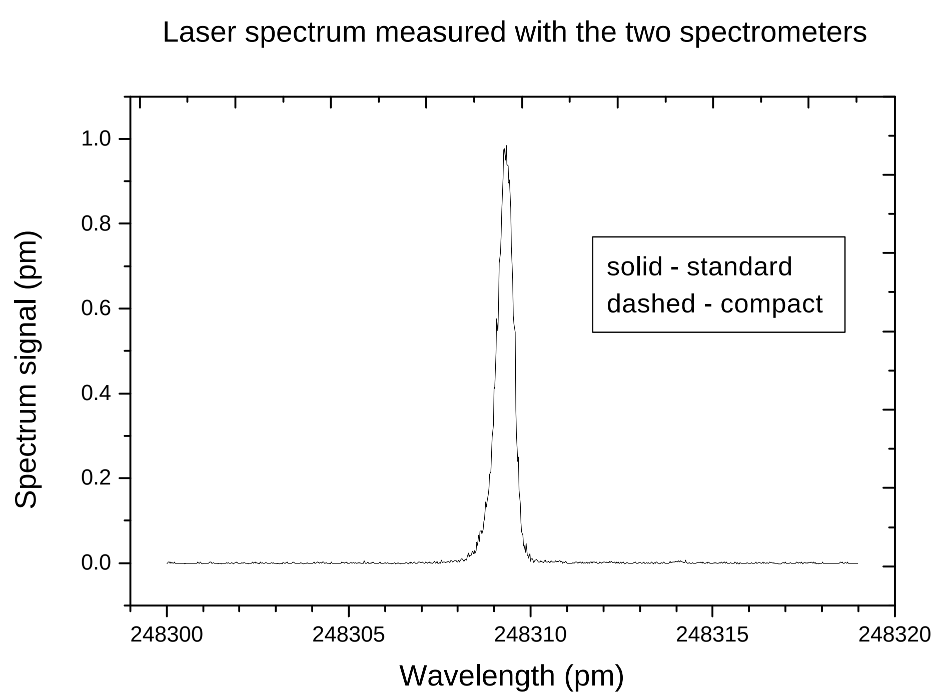

Fig. 7. Comparison of Cymer ELS-5000 laser spectrum measured with new compact grating spectrometer and Cymer standard high resolution grating spectrometer.

5. COMPACT HIGH RESOLUTION ETALON SPECTROMETER

As we discussed earlier, the conventional etalon spectrometer, as described by eq. (1) - (4) can not be directly used to measure spectrum tails due to the lack of resolution. However, the situation is quite different if the double-pass configuration is used. That is, the light goes through the etalon two times. In this case the equation (1) transforms into:

$$I_t = I_0 / (1 + (2F/p)^2 \sin^2 (d/2))^2 \ . \qquad (7)$$

The other eqs. (2) - (4) remain the same for double-pass configuration. The slit function of this modified etalon is presented in Fig. 8 along with slit functions of single pass etalon spectrometer and diffraction grating spectrometer. One can see, that the resolution of double pass etalon spectrometer is substantially increased, especially in the tails of slit function. In fact, this slit function is now looks similar to the slit function of the grating spectrometer. Table 1 summarizes slit functions for all three spectrometers.

Table. 1. Calculated slit functions for different high resolution spectrometers

Spectrometers	$\Delta\lambda_{FWHM}$	$\Delta\lambda_{95\%\ int}$
Single pass etalon spectrometer	0.13 pm	1.58 pm
Double pass etalon spectrometer	0.09 pm	0.25 pm
Double pass grating spectrometer	0.094 pm	0.23 pm

About 5X improvement in spectrometer resolution for $\Delta\lambda_{95\%\ int}$ measurements is achieved when double pass configuration is used. The slit function of the new etalon spectrometer is now similar to that of high resolution grating spectrometer, but the size of the former is substantially smaller. In fact, the size of this new spectrometer is similar to the size of conventional single pass etalon based spectrometer. Therefore, it can be easily installed in the laser and used in the field for accurate bandwidth monitoring. This spectrometer, is also capable of either single shot spectrum measurements or averaged over exposure window. We tested this spectrometer with 10-bit EG&G Reticon digital camera but higher resolution cameras can be used for better accuracy.

Fig. 9 shows a laser spectrum measured with new spectrometer as compared with Cymer standard high resolution grating spectrometer. These are spectrums as measured, with no deconvolution. The agreement between the measurements is quite good. $\Delta\lambda_{FWHM}$ values for double pass etalon and grating spectrometers are 0.65 and 0.62 pm, while $\Delta\lambda_{95\%\ int}$ values are 1.67 and 1.70 pm correspondingly.

6. CONCLUSION

The presented results show that the two new kinds of spectrometers, compact high resolution grating spectrometer and double pass etalon spectrometers both allow to accurately measure the excimer laser spectrum. Both $\Delta\lambda_{FWHM}$ and $\Delta\lambda_{95\%\ int}$ can be measured without deconvolution, which substantially increase the accuracy and reliability of the data. At the current stage of development, the compact grating spectrometer can be done to exactly match the performance of the bulky stationary high resolution grating spectrometer, but it is significantly smaller in size. This grating spectrometer can be now used as a field

tool, but more development is needed in order to install it in the laser. On the other hand, we show that double pass etalon spectrometer can also match performance of high resolution grating spectrometer and it can be made very compact. As a result, it can already be installed in a microlithography excimer laser or can be used as a field service tool. This will allow very accurate bandwidth control of the excimer laser and help to avoid costly yield problems.

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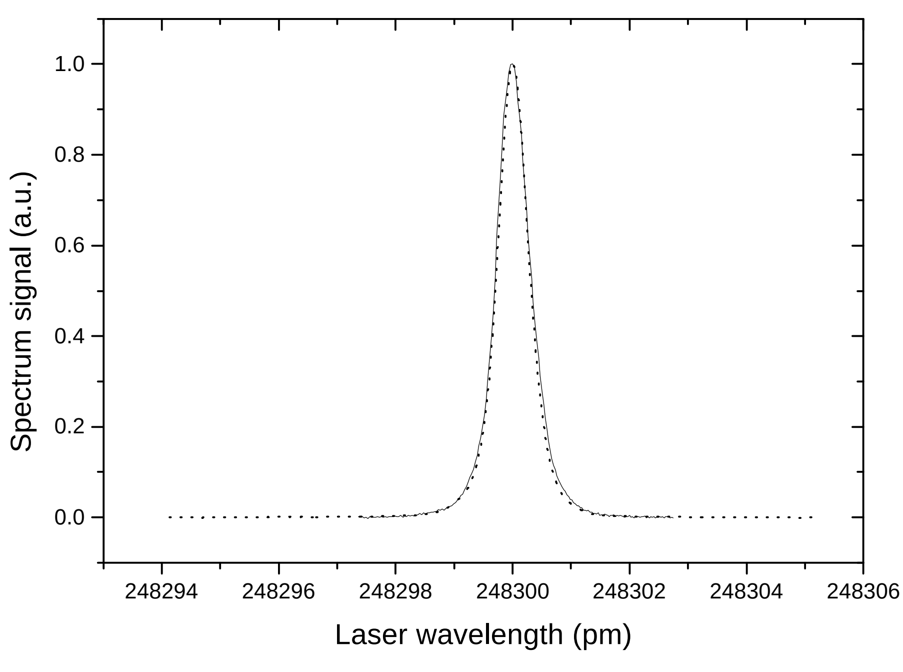
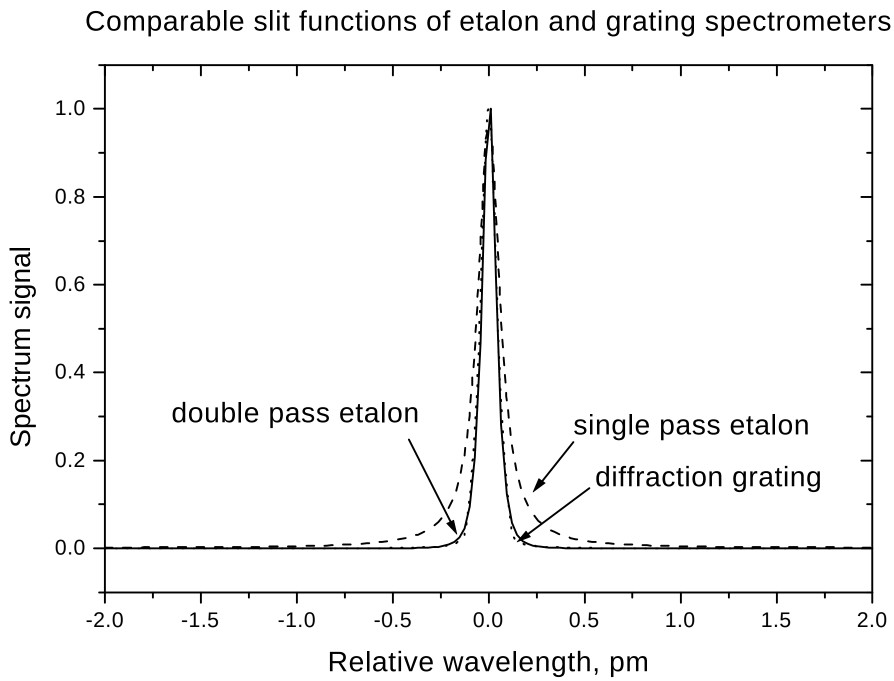


Fig.9. Cymer ELS-5000 laser spectrum measured with double pass etalon spectrometer

(solid curve) and high resolution grating spectrometer (dotted curve).
For grating spectrometer $\Delta\lambda_{FWHM} = 0.62$ pm and $\Delta\lambda_{95\%\ int} = 1.70$ pm;
for double pass etalon spectrometer $\Delta\lambda_{FWHM} = 0.65$ pm and $\Delta\lambda_{95\%\ int} = 1.67$ pm.



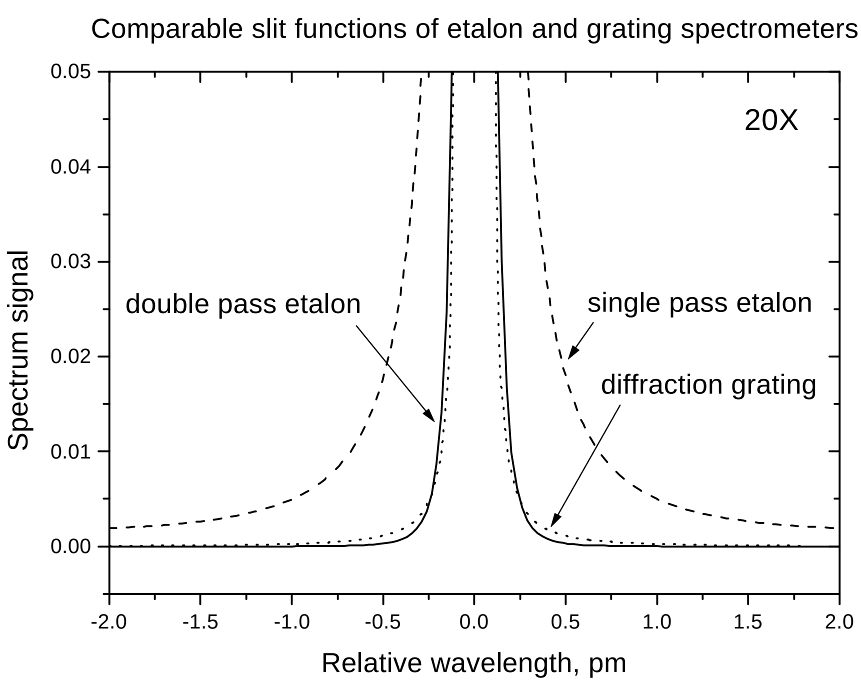


Fig. 8. Calculated slit functions of double pass etalon spectrometer (solid), single pass (conventional) etalon spectrometer (dashed), and diffraction grating spectrometer (dotted).